

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE (DD-MM-YYYY) 20-04-2004		2. REPORT TYPE REPRINT			3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE  First ground-based OI 630 nm optical measurements of daytime cusplike and F-region auroral precipitation					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
					5d. PROJECT NUMBER 2311	
6. AUTHOR(S) D. Pallamraju*, S. Chakrabarti*, R. Doe**, and T. Pedersen					5e. TASK NUMBER SD	
					5f. WORK UNIT NUMBER A4	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory/VSBXI 29 Randolph Road Hanscom AFB, MA 01731-3010					8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-VS-HA-TR-2005-1071	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/VSBXI	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited						
13. SUPPLEMENTARY NOTES REPRINTED FROM: Geophysical Research Letters, Vol. 31, L08807, doi:10.1029/2003GL019173, 2004. Copyright 2004, American Geophysical Union. *Center for Space Physics, Boston University, Boston, Massachusetts (Continued)						
14. ABSTRACT We have used a high-resolution (0.012 nm at 630 nm) imaging spectrograph to measure auroral emissions in daytime along the magnetic meridian from Sondrestrom Incoherent Scatter Radar (ISR) facility, at Kangerlussuaq, Greenland (67 deg. N, 51 deg. W; 74.5 deg N. Mag. Lat). Measured red line (OI 630 nm) brightness during a magnetically disturbed day (21 January 2001) shows emission enhancements starting at 1330 UT (1130 MLT) and reaching a four-fold enhancement above the normal dayglow brightness about two hours later. The onset enhancement, characterized by a sharp equatorward boundary, was measured concurrently with ISR Ne and Te, whose morphologies are generally indicative of cusplike precipitation. The 630 nm emission enhancements after 1518 UT correspond to a series of post-noon F-region arcs as measured by the ISR. Modeled 630 nm airglow brightness using IRSR data, agree well with both the brightness and time history of the daytime optical measurements.						
15. SUBJECT TERMS Airglow Aurora Dayglow Auroral cusp						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT		18. NUMBER OF PAGES	
a. REPORT UNCL	b. ABSTRACT UNCL	c. THIS PAGE UNCL	UNL		19a. NAME OF RESPONSIBLE PERSON Todd R. Pedersen	
					19b. TELEPHONE NUMBER (Include area code) (781) 377-2845	

Block 13 (Continued)

\*\*SRI International, Menlo Park, CA

# First ground-based OI 630 nm optical measurements of daytime cusplike and F-region auroral precipitation

D. Pallamraju,<sup>1</sup> S. Chakrabarti,<sup>1</sup> R. Doe,<sup>2</sup> and T. Pedersen<sup>3</sup>

**DISTRIBUTION STATEMENT A**  
Approved for Public Release  
Distribution Unlimited

Received 26 November 2003; revised 19 March 2004; accepted 24 March 2004; published 20 April 2004.

[1] We have used a high-resolution (0.012 nm at 630 nm) imaging spectrograph to measure auroral emissions in daytime along the magnetic meridian from Sondrestrom Incoherent Scatter Radar (ISR) facility, at Kangerlussuaq, Greenland (67°N, 51°W; 74.5°N Mag. Lat.). Measured red line (OI 630 nm) brightness during a magnetically disturbed day (January 21, 2001) shows emission enhancements starting at 1330 UT (1130 MLT) and reaching a four-fold enhancement above the normal dayglow brightness about two hours later. The onset enhancement, characterized by a sharp equatorward boundary, was measured concurrently with ISR  $N_e$  and  $T_e$ , whose morphologies are generally indicative of cusplike precipitation. The 630 nm emission enhancements after 1518 UT correspond to a series of post-noon F-region arcs as measured by the ISR. Modeled 630 nm airglow brightness using ISR data, agree well with both the brightness and time history of the daytime optical measurements.

**INDEX TERMS:** 0310 Atmospheric Composition and Structure: Airglow and aurora; 0358 Atmospheric Composition and Structure: Thermosphere—energy deposition; 2407 Ionosphere: Auroral ionosphere (2704); 2494 Ionosphere: Instruments and techniques; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions. **Citation:** Pallamraju, D., S. Chakrabarti, R. Doe, and T. Pedersen (2004), First ground-based OI 630 nm optical measurements of daytime cusplike and F-region auroral precipitation, *Geophys. Res. Lett.*, 31, L08807, doi:10.1029/2003GL019173.

## 1. Introduction

[2] The high-latitude edge of the auroral oval defines the transition from closed to open magnetic field lines in the Earth's magnetosphere—ionosphere (M-I) system. The day-side neutral line between the open and the closed field lines is defined as the magnetic cusp and is the region through which plasma from the Sun can have direct access into the Earth's upper atmosphere [e.g., *Shepherd*, 1979; *Smith and Lockwood*, 1996]. The dayside high-latitude ionosphere presents a plasma regime wherein multiple manifestations of M-I coupling coexist. Plasma density enhancements associated with the dayside convection reversal boundary [*Kelly*, 1985] and F-region photoionization (Tongue-of-ionization, TOI) are among the most significant dayside aeronomical features due to the global-scale electric field pattern.

<sup>1</sup>Center for Space Physics, Boston University, Boston, Massachusetts, USA.

<sup>2</sup>SRI International, Menlo Park, California, USA.

<sup>3</sup>Space Vehicles Directorate, Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts, USA.

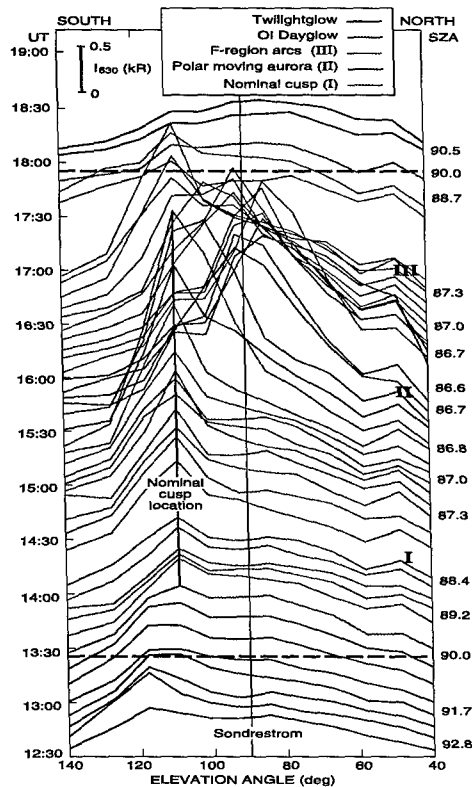
[3] On a more regional scale, persistent structured electron temperature enhancements, measured coincident with unstructured F-region electron density, have been related to cusplike precipitation [*Doe et al.*, 2001]. Herein cusplike refers to ISR measurement of persistent, field-aligned  $T_e$  enhancements coincident with little or no evidence of arc-related  $N_e$  structure. Optically, prior studies have characterized the cusp location as the region where the ratio of low-energy 630 nm emissions to high-energy emission (427.8 or 557.7 nm) is on the order of 3 or more [*Eather and Mende*, 1972; *Shepherd*, 1979; *Rodger et al.*, 1995]. Auroral arcs associated with dayside merging on the flanks of the cusp/cleft are also a significant regional signature of M-I coupling whose association with changing Interplanetary Magnetic Field (IMF) configuration and solar wind pressure has been studied extensively [e.g., *Sandholt et al.*, 1994]. Interest in obtaining new aeronomic measurements of the daytime ionosphere stem naturally from a desire to understand better the dynamics and morphology of the cusp as well as the TOI and daytime auroral arcs. Moreover, a daytime auroral emission measurement from the summer polar hemisphere opens up a new capability of investigating the conjugacy of aurora.

[4] All optical measurements of the cusp thus far have been made on the dayside of the auroral zone i.e., from locations where the ground and lower atmosphere are dark and are in the Earth's shadow. However, it is known that the characteristics of the dayside and daytime (Sun above the horizon) emissions are quite different, as the solar photon input energy is comparable to that of particles and the local time variation of the photon flux follows a diurnal pattern that is different from the magnetic local time (MLT) variation of the energetic particles [*Shepherd*, 1979]. For example, increased conductivity in the daytime ionosphere by photoionization has been suspected of causing the absence of frequently occurring nighttime auroral arcs in sunlit locations [*Newell et al.*, 1996].

[5] We operated the High-Resolution Imaging Spectrograph using Echelle grating (HIRISE) instrument [*Pallamraju et al.*, 2002] at the Sondrestrom ISR facility to understand better the dynamics of typical daytime auroral emission features and to explore the extent to which a ground-based spectrograph can characterize arc-related  $N_e$  enhancements and cusplike  $T_e$  enhancements. In this paper we report on the first ground-based 630 nm measurement of cusplike precipitation during daytime conditions. The collocated ISR measurements and airglow modeling corroborate our measurements.

## 2. Observations and Modeling

[6] HIRISE is a high-spectral-resolution imaging instrument that achieves daytime measurement capability by

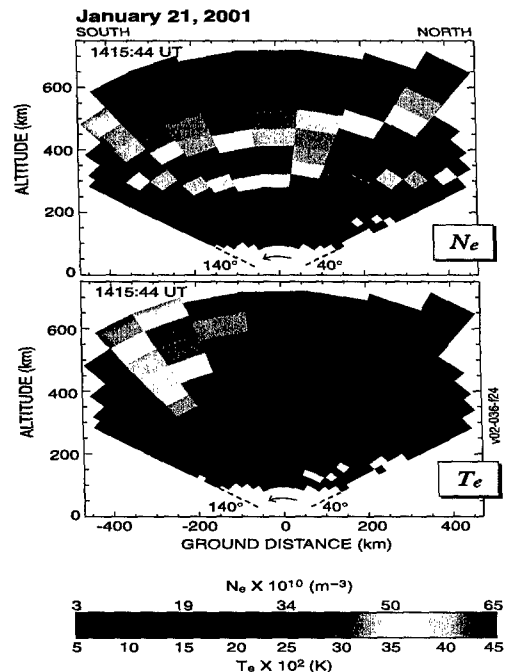


**Figure 1.** HIRISE measurements of 630 nm daytime emissions on January 21, 2001 along the magnetic meridian obtained from Sondrestrom (74.5° mag. lat.). Both IMF  $B_y$  and  $B_z$  were negative from 11–20 UT and  $K_p$  was 3. The curves other than in black correspond to daytime emissions (SZA at ground < 90°). Dotted horizontal lines represent the solar terminator on the ground. Emissions during time interval I (1330–1518 UT; blue) show daytime cusplike/magnetosheath precipitation at an elevation angle of 112° with a sharp equatorward boundary. Emissions during interval II (1518–1542 UT; magenta) and III (1542–1745 UT; green) correspond respectively to contributions from poleward moving aurora and to the equatorward movement of the F-region auroral arcs as substantiated by the ISR data.

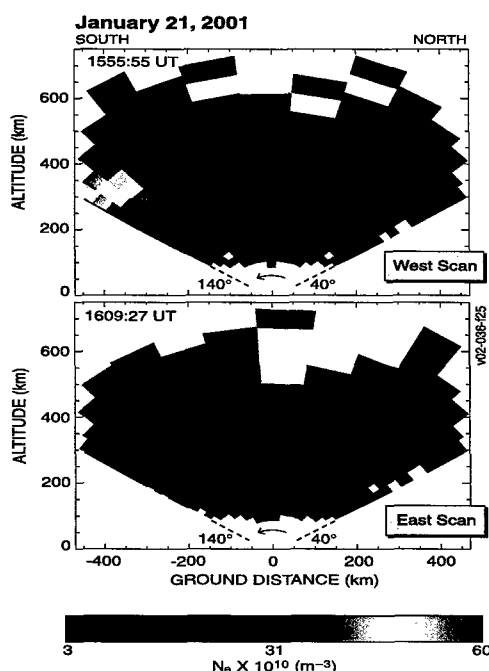
successfully removing the Fraunhofer contribution from the blue-sky spectrum [Chakrabarti, 1998; Pallamraju *et al.*, 2002]. The procedures employed for data reduction using HIRISE have been described in detail elsewhere [Pallamraju *et al.*, 2002]. Figure 1 shows the red line emissions at various elevation angles (measured from the North) along a magnetic meridian (333° azimuth) that was chosen to coincide with the ISR meridional scans from Sondrestrom on January 21, 2001. HIRISE images were integrated for 5 minutes, binned at an angular resolution of 10° (8–20 rows of data from each image were coadded depending on the elevation angle of the  $1 \times 8$  on-the-chip-binned image) in order to increase the signal-to-noise ratio, SNR, (the measurement uncertainties vary from 3% to 18%). The dashed black lines in this figure (before 1325 and after 1754 UT) correspond to twilighttime (solar zenith angle, SZA, on the ground > 90°) 630 nm airglow emissions, while the rest of the data is obtained during daytime (SZA < 90°). During the time interval I (1330–1518 UT, in blue) column emission

rates along the 112° elevation angle (22° south of zenith) increased gradually from around 1,200 R to 3,200 R over a dayglow background of around 800 R and showed a sharp southward (equatorward) boundary in the emissions. During this period the emissions northward and southward of this elevation angle do not show any such increase in brightness. After 1518 UT, the peak in the emission during interval II (magenta) shifts poleward until 1542 UT. At the end of interval II, a southward motion in the emissions is observed during interval III (green) until 1745 UT, which is coincident with the movement of an F-region auroral arc as seen in the ISR data (discussed in section 3).

[7] Coordinated  $N_e$  and  $T_e$  measurements were made by scanning the ISR along the magnetic meridian (azimuth 333°) from 1230 to 1454 UT followed by alternating scans tipped 25° to the West and East of the meridional plane from 1457 to 1801 UT. 320  $\mu$ s pulses established a maximum range resolution of 48 km along any look direction. This scan mode, designed to provide a constant ground-track distance per record, has angular resolutions that vary from 4° to 16°. Recovered autocorrelation functions from 10-s integrations yielded 15 angular samples per scan with sufficient SNR to ensure relative  $N_e$  error no greater than 15% and absolute  $T_e$  error no greater than 500 K. For 11 consecutive scans from 1352 to 1515 UT, a relatively unstructured F-layer was measured coincident with a persistent, latitudinally localized  $T_e$  enhancement (>4500 K)—an observation consistent with low-energy cusplike precipitation [Doe *et al.*, 2001]. Figure 2 shows ISR measured  $N_e$  and  $T_e$  scans during this cusplike event at 1415 UT. By 1555



**Figure 2.** Sample ISR meridional scans of  $N_e$  (top panel) and  $T_e$  (bottom panel) at 1415 UT. The arrow indicates the radar scan-direction. Notice the  $T_e$  enhancement up to about 4500 K in a narrow region around 30° south of zenith in 300–500 km, but no corresponding structuring in the  $N_e$  in any of the scan-directions, which is a characteristic signature of cusplike precipitation in the ISR measurements observed during interval I.



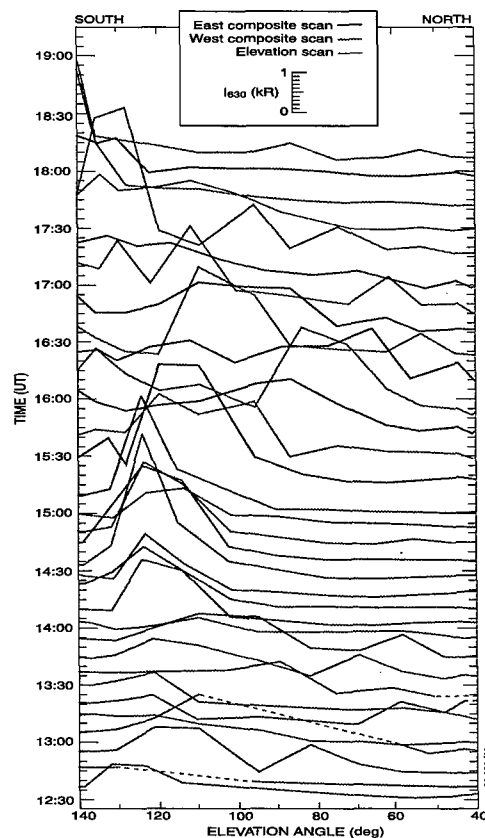
**Figure 3.** Typical ISR  $N_e$  scans showing F-region arc related  $N_e$  enhancements in interval III. Notice a 3–4 fold increase in electron density around 300 km at 1555 UT in the Northwestern direction, which moves towards Southeast of the HIRISE view direction by 1609 UT.

UT, the localized  $T_e$  morphology had vanished and the laminar  $N_e$  structure (Figure 2) gave way to a structured F-region arc event (Figure 3). In order to predict a maximum 630 nm airglow signatures corresponding to these plasma measurements, range-resolved  $N_e$  and  $T_e$  were used to calculate 630 nm volume emission rate ( $\eta_{630}$ ) due to chemical recombination of  $O_2^+$  and thermal excitation of  $O(^1D)$  using MSIS-90 [ $O_2$ ], an airglow branching ratio of 1, electron quenching and Einstein coefficients given by Torr and Torr [1982], and the prescription for thermal excitation of  $O(^1D)$  given by Rees and Roble [1975]. No auroral excitation component has been included, which may result in an underestimate of red line emission during the F-region arc event.  $\eta_{630}$  values were integrated along a given line-of-sight for each scan to recover surface brightness and are shown in Figure 4.

### 3. Discussion and Conclusions

[8] 630 nm model emissions (Figure 4) show an increase in brightness along  $125^\circ$  elevation angle and with a sharp equatorward boundary during 1330–1515 UT (blue lines) similar to those observed by HIRISE in time interval I. Throughout this period, ISR  $N_e$  data show an absence of E-region density structure and hence, the HIRISE red line emissions must originate from the F-region alone. There is an apparent systematic discrepancy between the elevation angles for the peak ISR cusplike features ( $125^\circ$ ) and the peak emission features in HIRISE ( $112^\circ$ ). Further, at 1418 UT, we note that the ISR model predicts 4,000 R of 630 nm emissions while HIRISE measured the brightness to be 3,200 R at 1513 UT. There are times when the measured emissions are larger than the model estimates.

This discrepancy between the locations and times of emission peaks might be due to combined effects of (a) a small misalignment between the orientations of the HIRISE slit with the ISR scan direction when their respective fields-of-view are projected to F-region altitudes, (b) errors in the angle calibration of HIRISE fore-optics (the spatial mapping is non-linear for any all-sky imaging system) and (c) uncertainties in model estimates. Most importantly, it should be noted that there are no additional peaks in emissions along the meridian in either measurements or the model predictions during this interval (I) indicating that both the optical measurements and ISR are measuring the same cusplike emission features, but possibly at a small distance apart. Additionally, the differences in time scales for one meridional ISR airglow model emission estimate of 150-s (fifteen individual estimates of 10-s each along an elevation angle) and HIRISE airglow measurements of 5 minutes (of continuous time-integration along the meridian) in conjunction with the lifetime of at least 110 s for  $O(^1D)$  complicate detailed point-by-point brightness



**Figure 4.** Model red line emissions obtained using the ISR-measured  $N_e$ ,  $T_e$  and MSIS neutral densities as inputs. The blue lines are model estimates in a viewing geometry similar to the HIRISE measurements. Notice the similarity of these plots with the HIRISE measured cusplike emissions (during interval I) showing a confined enhancement region with a sharp equatorward boundary. The purple and orange plots representing model emissions along the scans tipped  $25^\circ$  towards East and West of magnetic meridian show signatures of poleward moving auroral forms (during interval II) followed by the equatorward movement of F-region auroral arcs during interval III as indicated in Figure 1.

comparison. Moreover, as mentioned above, the airglow branching ratio, electron quenching coefficients and thermal excitation models were all chosen to estimate the maximum 630 nm airglow emissions (considering the uncertainties in the chemical reaction rates, collision cross-sections and the measured inputs into the model emissions, it is reasonable to expect a 20% uncertainty in them). From the dayside optical measurements, the cusplike/magnetosheath precipitation signatures are shown to be (a) a steady buildup of red line emissions in one location with (b) a sharp equatorward boundary in the emissions possibly due to the open and closed magnetic field line boundary [e.g., Milan *et al.*, 1999] (as seen during interval I) followed by (c) poleward moving auroral forms [e.g., Moen *et al.*, 2002] (as seen during interval II). Striking similarities in the dynamics (during intervals I and II) between our optical measurements, previous studies and our model emission estimates (Figures 1, 2 and 4) provide support for our conclusion that the daytime optical measurements accurately detected cusplike/magnetosheath precipitation during the period from 1330–1518 UT.

[9] The time interval III (1542 to 1745 UT) in Figure 1 shows intense emissions presumably due to the ISR detected F-region arcs. Figure 3 shows typical arc signatures of latitudinally narrow  $N_e$  structure (altitude > 200 km). A high F-region  $T_e$  enhancement collocated above the arc (not shown) was measured as well. These measurements stand in contrast to the relatively unstructured TOI  $N_e$  structure (density peak around 300 km) observed during the time interval I. The apparent location of the arc in these West (1555 UT) and East (1609 UT) scans can be interpreted as a dynamic arc moving southward or as a stationary arc with its primary axis rotated slightly eastward from a purely zonal orientation.  $T_e$  measurements during this interval III (not shown here) do not show any latitudinal structures as in Figure 2. HIRISE measurements show emission enhancements a few degrees north of zenith around 1605 UT, most likely corresponding to this arc. Model emissions along the West scan (orange) show larger brightness compared to the scan along the East (purple), while the HIRISE measurements (green, Figure 1) show a brightness between these two scans indicating that the arc was stronger West of the meridian. Both the HIRISE and the model emissions show equatorward movement of such arcs. Such striking similarities in the dynamics between HIRISE measurements, ISR data and model emissions (Figures 1, 3 and 4) support our conclusion that the increase in optical red line emission brightness during interval III is due to the F-region arcs.

#### 4. Summary

[10] We report on the first ground-based 630 nm measurements of cusplike precipitation during daytime condi-

tions as corroborated by concurrent measurements of  $N_e$  and  $T_e$  by collocated ISR and airglow modeling using those data. Signatures of F-region auroral arcs are also obtained as verified by the ISR data. HIRISE thus emerges as a powerful tool for studying cusp emissions and daytime aurora/airglow from the ground regardless of solar illumination conditions.

[11] **Acknowledgments.** This work was supported by NSF grants ATM-0097064, ATM-0077678, ATM-0209676 and AFOSR task 2311AS. Research support at SRI International was supported by NSF cooperative agreement ATM-9813556.

#### References

- Chakrabarti, S. (1998), Ground-based spectroscopic studies of sunlit airglow and aurora, *J. Atmos. Solar-Terr. Phys.*, **60**, 1403–1423.
- Doe, R., J. D. Kelly, and E. R. Sanchez (2001), Observations of persistent dayside F region electron temperature enhancements associated with soft-magnetosheathlike precipitation, *J. Geophys. Res.*, **106**, 3615–3630.
- Eather, R. H., and S. B. Mende (1972), Systematics in auroral Energy spectra, *J. Geophys. Res.*, **77**, 660.
- Kelly, J. D. (1985), Incoherent scatter radar observations of the cusp, in *The Polar Cusp*, edited by J. A. Holtet and A. Egeland, pp. 337–348, D. Reidel, Norwell, Mass.
- Milan, S. E., M. Lester, S. W. H. Cowley, J. Moen, P. E. Sandholt, and C. J. Owen (1999), Meridian scanning photometer, coherent HF radar, and magnetometer observations of the cusp: A case study, *Ann. Geophys.*, **17**, 159–172.
- Moen, J., I. K. Walker, L. Kersley, and S. E. Milan (2002), On the generation of cusp HF backscatter irregularities, *J. Geophys. Res.*, **107**(A4), 1044, doi:10.1029/2001JA000111.
- Newell, P. T., C.-I. Meng, and K. M. Lyons (1996), Suppression of discrete aurorae by sunlight, *Nature*, **381**, 766–767.
- Pallamraju, D., J. Baumgardner, and S. Chakrabarti (2002), HIRISE: A ground-based High Resolution Imaging Spectrograph using Echelle grating for measuring daytime airglow and auroral emissions, *J. Atmos. Solar-Terr. Phys.*, **64**, 1581–1587.
- Rees, M. H., and R. G. Roble (1975), Observations and theory of the formation of stable auroral red arcs, *Rev. Geophys. Space Sci.*, **13**, 201–242.
- Rodger, A. S., S. B. Mende, T. J. Rosenberg, and K. Baker (1995), Simultaneous optical and HF observations of the ionospheric cusp, *Geophys. Res. Lett.*, **22**, 2045–2048.
- Sandholt, P. E., C. Farrugia, L. Burlaga, J. Holtet, J. Moen, B. Lybekk, B. Jacobsen, D. Opsvik, A. Egeland, R. Lepping, A. Lazarus, T. Hansen, A. Brekke, and E. Friis-Christensen (1994), Cleft auroral activity in relation to solar wind dynamic pressure, interplanetary magnetic field  $B_z$  and  $B_y$ , *J. Geophys. Res.*, **99**(A9), 17,323–17,342.
- Shepherd, G. G. (1979), Dayside cleft aurora and its ionospheric effects, *Rev. Geophys.*, **17**, 2017–2033.
- Smith, M. F., and M. Lockwood (1996), Earth's magnetospheric cusps, *Rev. Geophys.*, **34**, 233–260.
- Torr, M. R., and D. G. Torr (1982), The role of metastable species in the thermosphere, *Rev. Geophys. Space Sci.*, **20**, 91–144.
- D. Pallamraju and S. Chakrabarti, Center for Space Physics, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA. (dprraju@bu.edu)
- R. Doe, SRI International, Menlo Park, CA, USA.
- T. Pedersen, Space Vehicles Directorate, Air Force Research Laboratory, Hanscom Air Force Base, MA, USA.